GRAVEL AS A RESISTANT ROCK[1]

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INTRODUCTION

The thesis which this paper will endeavor to establish may be stated as follows: *Gravel, in its relation to the agencies of denudation, is, under certain geological conditions, a highly resistant rock. To these agencies it will, in general, offer greater resistance than ordinary igneous or sedimentary rocks, with a few possible exceptions.* On the validity of this thesis hinge important deductions as to the normal course of topographic development in cases where such gravel plays a prominent part in the geological structure of a region.

It is my purpose (1) to point out the theoretical reasons for the resistant nature of gravel deposits; (2) to show from an actual occurrence in nature that the gravels do behave as the theoretical considerations would lead us to expect; and (3) to sketch, by way of suggestion, the normal course of development of topography in a region where alluvial fans of coarse material are accumulating at the base of mountains. By way of suggestion there will be further a brief application of the principles brought out to certain well-known topographic features.

Except for the descriptive portion of the paper, which will be clearly distinguished, the article is an analytical study made mainly for the purpose of determining the influence of certain types of rocks upon the processes and rate of denudation, and of calling attention to what appears to be a normal cycle of denudation and the topographic development of mountains in an arid region, and to a lesser extent in a humid region as well.

At the present time no attempt will be made to review exhaustively the literature of the subject.

[1] Published by permission of the Director of the U.S. Geological Survey.

RESISTANT QUALITIES OF GRAVEL

It is natural to look upon gravels as weak rocks which may easily be removed by the agencies of denudation. While this is doubtless true for sand or possibly even for fine gravel, it is a view which does not hold true of gravel of a coarser nature such as accumulates at the base of mountain ranges either in arid or humid climates, or of river gravels of the coarser type such as the Lafayette gravels of the Mississippi Valley.

There are two essential reasons for the resistant quality of gravel as regards denudation. These are: (1) the selected nature of the material; (2) its porosity. As regards the first of these, gravel is a composite rock made up of units, each of which is selected on the basis of its ability to withstand the action of the agencies of destruction to which all rocks are subjected. These agencies of disintegration are both mechanical and chemical. With respect to the mechanical, gravel may be looked upon as a residue which has survived the rolling, pounding, and abrasion incident to its transportation along the stream course, an experience which, if the journey be a long one, effectively grinds down and destroys all but the most resistant of the materials subjected to it.

From the standpoint, also, of rock *decomposition* gravel is particularly resistant, for it is a rock whose component materials are severally selected on the basis of their ability to withstand such decomposition. In a region of normal development where there has been no interference with normal conditions by such accidents as glaciation, the stream gravels represent, in the main, only rocks or fragments of rocks which, by virtue of their resistant qualities, have been able to survive unchanged the decomposition and mechanical disintegration which has effectively destroyed the rock surrounding them. They have undergone successfully the ordeal which has destroyed the neighboring rock. They are therefore still able to resist further subjection to the action of the same agencies of change.

Physically also, gravel is especially fitted to resist disintegration because in it the component fragments are reduced to compact units unbroken, as a rule, by fractures or other lines of weakness. The surfaces are generally smoothed and give little opportunity for

the attack of frost or for the entrance of percolating water, while the comparatively small size of the units diminishes the activity of insolation as a disintegrating agent. For these reasons, while a massive quartzite, for instance, may be as resistant as gravel to disintegration due to either mechanical abrasion or chemical decomposition, it will be more likely, especially if in larger masses, to suffer more from the effects of insolation and frost.

From the foregoing it is clear that stream gravels, particularly the coarser ones, may properly be looked upon as *concentrates* of the most resistant elements of the rocks from which they are derived. It follows that a gravel of such a nature will be more resistant to the agencies of disintegration than the original rocks. From its very nature and origin a gravel deposit should be expected to offer great resistance to the normal agencies of sub-aerial denudation. This resistant quality is particularly significant in the development of the topography of gravel deposits, since, disintegration being at a minimum, bodily removal of the component units of the gravel is necessary for their reduction; and, as we shall point out later, bodily removal, too, is at a minimum except along the immediate courses of good-sized streams. In the latter situations this may be readily accomplished, but away from the actual stream course the removal of the material must necessarily be very slow. The importance of this point in relation to the dissection of the alluvial fans along the base of a mountain range will be more fully elaborated on a subsequent page.

The second characteristic of gravels which makes them resistant to the disintegrating and erosive forces which would wear them down is their porosity and the consequent comparatively slight development of surface drainage on the gravel areas. A gravel deposit of moderate coarseness offers the maximum of favorable conditions for the absorption and storage of the rain which falls upon its surface. This hinders the formation of small surface streams, and since, as we have seen, disintegration is at a minimum, and the removal of the gravel is almost entirely dependent upon the transporting action of such streams, the gravels are doubly protected from removal.

From the foregoing theoretical considerations we should expect

that gravel would be one of the most resistant of rocks as far as its relation to the processes of disintegration and removal is concerned.

Compare, for instance, the relative ease with which weathering and erosion break up and remove the rocks from an area of granite and from one of moderately coarse gravels in a similar situation. In the case of the granite there is always a greater or less number of joints or fissures through which water may enter and perform its work of disintegration either by direct chemical decomposition or by the subsidiary agency of frost. In contrast to this there are the smooth, usually fissureless surfaces of the gravel units. The granite is made up of a variety of minerals, some of which are easily attacked by the weathering agents. Some, it is true, are as resistant as the most resistant components of the gravel but in every case these are small, being limited in size by the texture of the granite. There is too, in a rock of complex mineral composition, the factor of pulling apart of the mineral grains by differential expansion and contraction.

The less resistant minerals, by weathering away and breaking down, leave the harder and more resistant ones free to be removed by the surface waters. Since, in general, the size of the grains is comparatively small, in a granite scarcely exceeding one centimeter in diameter, the resistant materials are readily removed by the streams in the form of sand, while the products of the more thorough disintegration of the less resistant minerals are easily carried away in suspension or solution or may even be, in considerable measure, picked up and carried off by the winds.

Thus we see that a granite is much more vulnerable to the attacks of the weathering agencies than a coarse gravel. What is true of granite is also true in varying measure of any of the less resistant sedimentary or igneous rocks, such as shale, soft sandstone or limestone, diorite, etc. In the case of quartzite and certain of the lavas it is a question which would disintegrate more rapidly, these or the gravel. The latter has in its favor, as a resistant rock, the factor of porosity and the slight effect of insolation.

All the above considerations apply particularly when the slope is low. On very steep slopes the lack of coherence of the gravel,

FIG. 1.—A portion of the Silver City quadrangle, N.M., showing the features described in the text. The gravel area is shown by the dotted pattern.

combined with the effect of gravity and the rapid mechanical erosion, would doubtless cause more rapid removal of gravel than of granite on account of the dominance of the factor of bodily transportation.

PIEDMONT GRAVELS NEAR SILVER CITY, NEW MEXICO

Near the town of Silver City, N.M., best shown between there and the smaller town of Central, seven miles directly to the east (see *U.S.G.S.*, Silver City quadrangle), there lies a gravel deposit of Piedmont nature which presents points of particular interest in connection with the thesis just presented. The road from Silver City to Central follows closely along the inner or mountainward margin of this deposit (Fig. 1) which extends from here southward for 40 or 50 miles as a part of the gravel fan of a great interior basin which, with its tributary basins, covers a large area in the southwestern part of the state.

The gravel plateau, as it will be called, in the portion under consideration between Silver City and Central, has a slope to the south of about 100 ft. per mile and strikes approximately east and west. It is characterized by great uniformity and evenness as seen from any point on the plateau surface. One sees merely a monotonous plain of gravel, horizontal as one looks to the east or west, but sloping always toward the south. This appearance of great evenness applies, however, only to the remnants as seen from a point on the plateau surface, for, particularly near the northern or mountainward margin, it is considerably dissected by streams which, flowing outward from their sources in the mountains, have carved long, usually nearly straight and parallel valleys down the dip of the plateau (Fig. 2). These valleys are cut to a depth of about 150 ft. at the maximum. As one follows them out toward the desert plain they gradually become shallower and finally disappear altogether. Degradation there gives place to aggradation.

The gravel of the plateau is composed of rocks found in place in the mountains and the whole character and relationship of the deposit points clearly to its origin as a Piedmont accumulation of gravel spread out from the adjacent mountains to the north at some earlier time before dissection set in.

While from its nature as a Piedmont accumulation, the gravel of the plateau has not suffered complete elimination of the less resistant elements, it is, nevertheless, an assorted mass in which rocks of the more resistant kinds strongly predominate. A list of a few of the more common of these will give a fair idea of the nature of the gravel and of the extent to which the more resistant rocks dominate. The list follows: green quartzite, white quartzite, light-colored rhyolite, basalt, diorite, epidotized granodiorite, garnet rock, and magnetite from the Hanover ore deposits.

FIG. 2.—Looking down one of the valleys which crosses the gravel plateau from the lowland to the desert beyond. Note particularly the character of the valley; its narrowness and lack of tributaries. Compare this with the broad valleys developed on the bed-rock of the lowland as shown in Fig. 3. Lone Mountain in the background.

The coarseness of the material varies. Individual bowlders of large size are buried in a matrix of smaller bowlders, pebbles, and sand. This combination gives a rock of very porous nature, capable of absorbing quickly the water which falls upon it. At the same time the removal of the finer material of the matrix leaves the coarser bowlders and pebbles concentrated at the surface where they form a very effective protective covering—effective against either rain erosion, wind, or decomposition.

The most conspicuous feature in connection with this plateau is the fact that it is now separated by a lowland from the moun-

tains which supplied the material for its construction. Nor is this lowland the site of a stream valley. It runs, on the contrary, parallel to the strike of the beds and is crossed directly by the course of all the streams which flow from the mountains out through the dissected plateau to the desert beyond.

A good idea of the nature of the lowland may be gained from the photograph, Fig. 3 (see also the map, Fig. 1). This shows the lowland in the foreground and to the left; the even-topped gravel plateau on the skyline; and, sloping down toward the observer,

FIG. 3.—Looking southeast from the Central road three miles east of Silver City. This view shows clearly the even-topped gravel plateau and its inward slope toward the lowland in the foreground.

the inner scarp of the plateau facing the lowland at the divides between streams. The view is looking southeast from the Central road three miles east of Silver City.

On the interstream ridges the difference in elevation between the inner lowland and the tops of the plateau surface varies between 50 and 100 ft. In going northward along the tops of the divides, toward the mountains, one must travel from $\frac{1}{2}$ to 2 miles before he again encounters ground as high as the tops of the gravel plateau. If the dip slope of the plateau surface is projected across the lowland toward the mountains the present land surface is not intersected within a distance of about 4 miles, on the average, from the

general line of the gravel plateau. Such a projection may be assumed to be a minimum original slope, for it makes no allowance for an increased slope of the plateau surface nearer the mountains, as must have been the case if the gravels once covered the lowland. This feature is illustrated in the two profiles shown in Fig. 4, drawn to scale from two different points well out on the plateau northward across the lowland to the base of the mountains.

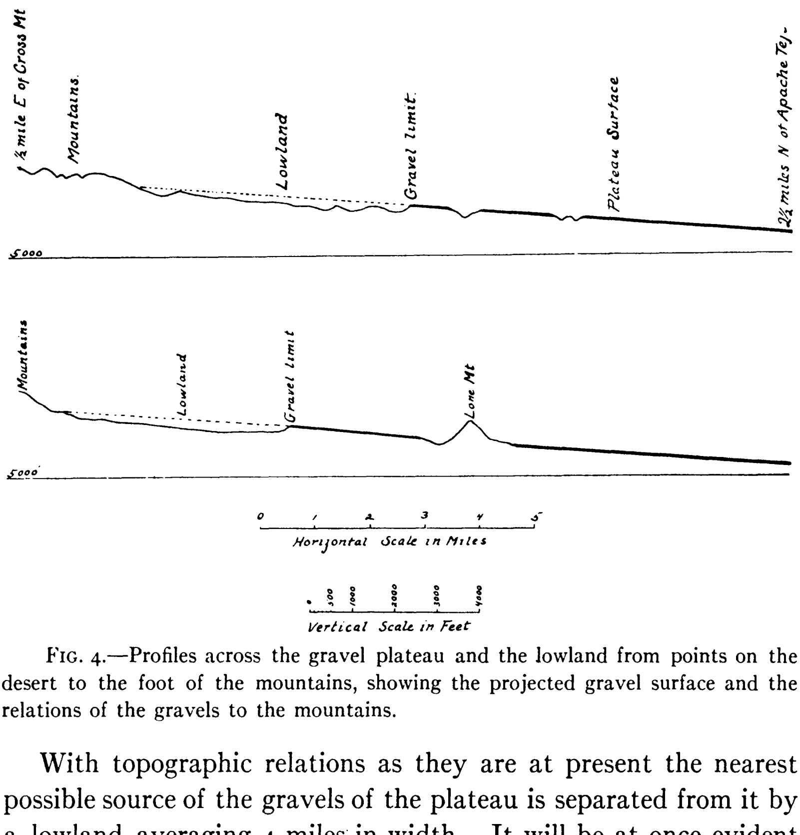

FIG. 4.—Profiles across the gravel plateau and the lowland from points on the desert to the foot of the mountains, showing the projected gravel surface and the relations of the gravels to the mountains.

With topographic relations as they are at present the nearest possible source of the gravels of the plateau is separated from it by a lowland averaging 4 miles in width. It will be at once evident that, at the time of the formation of the plateau, the lowland could not have existed in its present relation. Any one of three things may have happened to bring about present conditions: (1) The gravels may have been removed by erosion from the area between their present limit and the mountains; (2) there may have been faulting by which the lowland was relatively lowered; or (3) the mountains

may have worn back and the lowland developed by differential erosion since the deposition of the gravels.

Opposed to the first of these alternatives is the fact that the gravel plateau ends abruptly along a relatively straight line. There are no outliers of gravel between this general line and the mountains. It is highly improbable that streams flowing nearly parallel and not more than a mile apart should strip all signs of the gravels from the upper four miles of their course, while in their lower course, where they flow across the gravel plateau, they should be in relatively narrow valleys with almost no tributaries and should have done little more than to cut their way through the plateau without having been able to widen their valleys to any great extent (Fig. 2).

A second objection is the fact that the line of contact between the gravels and the underyling rock slopes upward toward the mountains at such an angle that it would intersect the projected line of the plateau surface at a point not far within the present limit of the gravels (see Fig. 5). In other words the gravels thin toward the mountains at such a rate that they would wedge out within a short distance from their present limit, and the lowland is accordingly developed in the bed-rock.

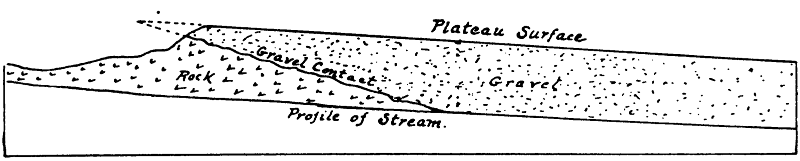

FIG. 5.—Sketch showing the relation between the gravels of the plateau and the underlying rock which indicates that the gravels never reached much nearer the mountains than now.

A third objection is raised by the fact that in the gravels of the plateau there are aggregations or nests of huge lava bowlders, some of them 15 feet in diameter, which indicates that the mountians must at one time have been closer, for bowlders of such size are too large to be carried far by water, particularly by water flowing on a slope of 100 ft. per mile, which is approximately that of the plateau surface.

The second alternative, faulting, seems highly improbable, for there is no evidence whatever of the presence of faults along the

line between the gravels and the lowland. At Silver City a tongue of the gravel plateau extends with accordant grade directly across the line of any fault which might have uplifted the gravels farther east. Further conclusive evidence of the lack of fault relationships of the lowland is furnished by the fact that the contact between the gravels and the underlying rock runs down the valleys and up across the interstream ridges in a perfectly normal manner, and with such wide divergence from a straight line as to preclude the possibility of an explanation by faulting.

The failure of the first two hypotheses to account for the inner lowland leaves only the third, that of differential erosion. This calls for, first, the formation of the plateau as a Piedmont plain of accumulation at the base of the mountains; later, the cessation of active aggradation, possibly because of a lowering of the mountains through erosion; the initiation of a degradational phase of activity; and finally, the gradual erosional retreat of the mountain front and the reduction of the intermediate land at a rate faster than that of the gravels, leaving them standing in their present relations.

Important in this connection is the nature of the rock composing the lowland. It is, in the main, a series of soft Cretaceous shales cut by dikes of a moderately resistant igneous rock. In parts of the lowland the shales are absent and the bed-rock is igneous. This, however, makes little difference in the nature of the resulting topography. Everything is worn down to a nearly uniform level lower than that of the gravels.

A discussion of all the possible causes of the change in the phase of activity from one of aggradation to one of degradation would be out of place here. Two such may, however, be mentioned. The first is change in climate, the second, a lowering of the mountains by erosion with consequent relative increase in the factor of decomposition, over that of disintegration and transportation, brought about by the lessened slope.

If the same process of differential erosion continues, the mountains will eventually become much reduced in height while the gravels, suffering less by erosion, will stand relatively higher and may finally come to dominate the topography of the surrounding

country. With respect to the drainage to the south, the extent to which this process can be carried is limited by the base level of the interior basin to which the streams are tributary.

A factor which must profoundly affect the topographic development of the whole region is the Gila River with its tributaries which, passing within 20 miles of Silver City, to the northwest, drains a large proportion of the mountain area. The Gila drains directly to the sea, and being a good-sized permanent stream, whose valley is some 1,600 ft. lower than the gravel plateau, it is actively pushing its headwaters southeastward into the drainage area of the interior basin in which the plateau is situated. The divide, in one place, now lies only 6 miles from the gravel plateau and is only 400 ft. higher. The Gila affords opportunity for the free removal of the waste from the mountains. Short and steep slopes combine to increase its effectiveness.

Eventually the normal outcome of processes now in operation should be that the mountains would become lowered; the interior lowland between the plateau and the mountains would, by capture, become tributary to the Gila; and the plateau itself, remaining higher on account of its superior resistance to erosion, would terminate in a scarp overlooking the lower lands to the north.

SIMILAR FEATURES IN OTHER REGIONS

Other areas are known where gravel deposits of a nature similar to those on the plateau east of Silver City occupy a similar topographic position and seem to show much the same history.

A good example, with which the writer is familiar, is the Bishop conglomerate of southwestern Wyoming and northeastern Utah. This represents a Piedmont gravel accumulation derived from the Uinta Mountains, and at one time skirting entirely round their base. Subsequent erosion has so lowered the mountains that over considerable areas, particularly at the eastern end, they are actually lower than the tops of the gravel-capped plateaus which represent the eroded remnants of the Piedmont gravel deposits. This condition has been described by the writer in an earlier paper.[1] Between

[1] "The Physiography of the Bishop Conglomerate, Southwestern Wyoming," *Jour. Geol.*, XVIII, No. 7 (1910), 601–32.

the mountains and the plateau are valleys sometimes 10 to 15 miles wide, and as much as 2,500 ft. deep (*ibid.*, p. 622). Other observers who have worked on the south side of the range report similar conditions there.

The resistant qualities of the gravel are particularly well illustrated by the Bishop conglomerate. The plateaus have remained with little change while general erosion has lowered the surrounding country nearly 1,000 ft. on the average.

In point of origin and later development, the Bishop conglomerate is thought to represent exactly the same type of phenomenon as we have described from the Silver City region; the only difference being that, in the former case, the process has been carried farther and the results are just so much the more striking.

CYCLE OF MOUNTAIN DEVELOPMENT

If the above analysis is correct, as it seems to be, both from the theoretical side and from field observation, the influence of gravel deposits is an important factor to be considered in the cycle of development of mountain topography. This cycle is admittedly complex, involving many factors, but for the purpose of clearly presenting the point especially in mind at the present time, it is not necessary to follow each of the factors involved. On the contrary, the consideration of the subject will be confined, as far as practicable, to a brief outline of the manner in which gravels, by reason of their selected nature, suffer less than other rocks.

At the initiation of the cycle of mountain development let us postulate the following ideal conditions: A mountain range, or simple fault block of moderately resistant and varied rocks sharply uplifted above the surrounding country. Free drainage from the foot of the mountains to some base level, either of interior or of exterior drainage, lying at a considerably lower elevation. In order to give the maximum of favorable conditions, we will postulate further that the climate is semi-arid so that vegetation plays a subordinate rôle.

Granting these initial conditions, and assuming that there are no further crustal movements, let us trace the development of the mountain range.

At first, with steep, exposed slopes, *disintegration*, through frost and insolation, and *erosion* will be rapid. The streams, while powerful enough to carry the loosened material down the steep slopes, will be unable to transport it across the lowland below. Piedmont fans of coarse gravel will accumulate along the mountain base. As time goes on the fans will continue to grow at the expense of the mountains. During this stage the fans are the seat of continual deposition, the mountains of continual waste and removal. Finally there must come a time when the mountains have become so lowered that the streams are no longer flowing over steep slopes. As this stage is approached, disintegration and decomposition within the mountain area will become relatively more important and the rocks will be reduced to a finer condition before being carried off. The streams will no longer be overburdened with sediment too coarse to be carried beyond the base of the mountain. At this point the upbuilding of the fans at the immediate mountain base must cease while the locus of deposition is shifted farther out because the stream load, being of a finer nature, may be carried to a greater distance before deposition occurs.

This is the turning-point in the history of the mountain range. From now on, both mountains and fans will be subject to denudation or degradation. If both the fans and the mountains were worn down at an equal rate, the whole area would merely lose in elevation without any marked change in the relations of mountains and gravels. Since, however, according to our thesis, the gravels will suffer from erosion less than the rocks of the mountains, differential erosion becomes an important factor. As the slopes decrease and decomposition plays an increasingly important rôle while the material furnished to the streams becomes finer and less in amount, the burden of the streams becomes less and they are able to cut where deposition was in progress before, and will sink their channels into the Piedmont fans.

Since the mountains are lowered faster than the gravels, a lowland will gradually develop, beginning first near the position of the inner margin of the gravel at the time of the change from aggradation to degradation. If the base level of the streams is sufficiently low, this lowland may eventually come to include the whole of the

mountain area. If the streams crossing the Piedmont gravel fans sink deeply enough they may finally cut entirely through the gravel into the underlying rock. In that case we will have a plateau between the streams, capped by gravels of a composition corresponding to that of the rocks of the lowland which occupies the site of the original mountains, but lying at a level higher than the summits of these mountains as they now exist.

Various combinations of factors will modify in different ways the course of development as sketched above, but the general principle involved should hold true, and the results should be in harmony with this principle as modified by the particular factors dominating in any one case.

EXAMPLES ILLUSTRATING THE TYPE OF DEVELOPMENT ABOVE OUTLINED

As examples of the influence of the slower differential erosion of gravel deposits the following may be mentioned: The region east of Silver City; the Uinta Mountains and the associated Bishop conglomerate, both described in the preceding pages. The Catskill Mountains of New York, in their relation to the old lowland to the east, are a possible illustration of the principle.